PUMP POWER MONITOR SYSTEM AND METHOD FOR GAIN CONTROL OF OPTICAL AMPLIFIER

CROSS REFERENCE TO RELATED APPLICATIONS

The present application claims priority to U.S. Provisional Pat. App. No. 60/230,019, entitled Pump Power Control of Raman Gain, filed September 5, 2000, which is hereby incorporated herein by reference in its entirety, which claims priority to U.S. Pat. App. No. 09/641,579, entitled Gain Control in Raman Amplifier, filed August 18, 2000, and which is also hereby incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention is directed to a pump power monitor method for gain control of an optical amplifier, and in particular, to a pump power monitor method for controlling the gain of an optical amplifier pumping at multiple, distinct wavelengths.

2. Technical Background

Raman amplification occurs when higher-energy or shorter wavelength, pump photons scatter off the vibrational modes of a materials lattice matrix, i.e. optical phonons, and

coherently add to lower-energy or longer wavelengths, signal photons. Typically, a pump laser is used to provide pump radiation through a Raman medium to generate stokes radiation in another wavelength range by Raman scattering. The stokes radiation is then used to amplify a source signal conducted through the Raman medium. A direct consequence of this is that Raman amplification can be realized at any wavelength in any optical fiber by correct choice of the wavelength of the optical pump.

Interest in developing applications for Raman amplification subsided when erbium-doped fiber amplifiers and other rare earth-doped amplifiers became known. Erbium-doped fiber amplifiers typically require less power to generate a given amount of gain when compared to Raman amplifiers. However, erbium-doped amplifiers effectively operate over only a limited wavelength band. While an erbium-doped fiber can be used for amplification in a wavelength band extending from 1530 nm to 1610 nm, such an amplifier configuration would require at least three erbium-doped fibers to cover this entire range. In comparison, Raman amplification allows amplification of the entire wavelength range within a single optical medium.

Raman amplification has become a viable commercial technology with demonstrations of wave division multiplexing near the zero-dispersion wavelength of dispersion shifted fibers. In such applications, typically referred to as Raman-assisted transmission, a pump light is launched into an optical fiber at inline amplifier sights in an opposite direction to that of the source signal, or the signal being amplified. The amplification is distributed along the transmission fiber with gain increasing exponentially near the output end near of the transmission fiber.

As distributed Raman-assisted transmission is rapidly becoming a commercial reality, several technical problems must be overcome. In contrast to erbium-doped amplifiers, there is little control or knowledge of the result and gain prior to installation due to several variables including variation in the effective area of a single fiber or multiple fibers combined within a particular span, pump wavelength attenuation, including that of the fiber(s) themselves as well as between the fiber(s) and the amplifier, and Raman gain coefficient of the fibers that are combined to cover the span.

Specifically, due to manufacturing variations in the magnitude of Raman gain coefficient fiber, effective area attenuation at the pump wavelength, power optimization is not

only necessary between fiber types but also within a particular fiber type. Another variable making control of gain and gain ripple difficult is the spectral variations within different fibers and particular fiber types. The spectral variations alone can cause gain ripple to be greater than 0.5 dB, and sometimes greater than 1dB. A further drawback is the manufacturing variability in the central pump power wavelength and thermal changes to the periodicity of the stabilizing fiber Bragg grating. Therefore, control of the amplification, including gain and gain ripple, within distributed Raman-assisted transmissions requires significant control, especially for transmission rates of 40 Gb/s for distances greater than 600 km.

SUMMARY OF THE INVENTION

This invention relates to a pump power monitor method for controlling the gain of an optical amplifier. More specifically, the present inventive pump power monitor method provides for gain control of an optical amplifier pumping at multiple wavelengths. Further, while the present inventive pump power monitor method is discussed with respect to Raman amplification, the method that may be implemented in conjunction with other optical amplifiers including, but not limited to, erbium-doped fiber amplifiers operating at multiple wavelengths.

In one embodiment, an optical fiber amplifier system includes an optical fiber adapted for use as an optical wave guide amplifier, and at least one optical pump optically coupled to the optical fiber, wherein the pump receives both a DC electrical input and an AC electrical input, and provides an optical pump power having both a DC optical power component and an AC optical power component to the optical fiber. The optical fiber amplifier system further includes a pump power detector optically coupled to the pump, and at least one controller connected to the pump power detector and adapted to determine the DC optical power component of the optical pump power, wherein the controller is adapted to adjust the DC electrical input to the pump.

In another embodiment, a Raman optical fiber amplifier system includes an optical fiber adapted for use as a Raman optical fiber amplifier, and at least one optical pump optically coupled to the optical fiber, wherein the pump receives both a DC electrical input and an AC electrical input, and provides an optical pump power having both a DC pump power component and an AC pump optical component to the optical fiber. The Raman optical fiber

amplifier system further includes a pump power detector optically coupled to the pump, and a controller operatively connected to the pump power detector and adapted to determine the DC optical power component of the optical pump power, and adjust the DC electrical input of the pump.

In addition, embodiments of the optical fiber amplifier system include controlling the gain of a single optical amplifier operating at a given wavelength, controlling the gain of an optical amplifier that includes multiple pumps operating at multiple wavelengths, individual control circuits for controlling the gain of each of the optical pumps associated with the amplifier, and a switching system for controlling multiple optical pumps operating at multiple at multiple wavelengths with a single control circuit.

Other embodiments include an optical communication system that utilizes the pump power monitor scheme, as well as a method for utilization of the pump power monitor scheme.

Additional features and advantages of the invention will be set forth in the detailed description which follows and will be apparent to those skilled in the art from the description or recognized by practicing the invention as described in the description which follows together with the claims and appended drawings.

It is to be understood that the foregoing description is exemplary of the invention only and is intended to provide an overview for the understanding of the nature and character of the invention as it is defined by the claims. The accompanying drawings are included to provide a further understanding of the invention and are incorporated and constitute part of this specification. The drawings illustrate various features and embodiments of the invention which, together with their description serve to explain the principals and operation of the invention.

Reference will now be made in detail to the present preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view of a pump power monitor system for controlling the gain of an optical amplifier embodying the present invention, including a single pump and a single control circuit;

Fig. 2 is a schematic view of a first alternative embodiment of the pump power monitor system for controlling the gain of an optical amplifier, including multiple optical pumps and multiple controlling circuits associated therewith;

Fig. 3 is a schematic view of the pump power monitor system for controlling the gain of an optical amplifier, including multiple optical pumps, an electrical switch and an associated clock timer;

Fig. 4 is a graph of gain vs. wavelength for the pump power monitor system of the present invention utilizing three wavelengths and six optical pumps;

Fig. 5 is a graph of gain vs. wavelength for the system of Fig. 4 adjusted to provide a 12 dB gain and a 0.8 dB gain ripple; and

Fig. 6 is a graph of gain vs. wavelength for the pump power monitor system of the present invention utilizing four optical pumps.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Additional features and advantages of the invention will be set forth in the detailed description that follows and will be apparent to those skilled in the art from the description or recognized by practicing the invention as described in the following description together with the claims and appended drawings.

It is to be understood that the forgoing description is exemplary of the invention only and is intended to provide an overview and an understanding of the nature and character of the invention as it is defined in the claims. The accompanying drawings are included to provide a further understanding of the invention and are incorporated and constitute in part of the specification. The drawings illustrate various features and embodiments of the invention, in which, together with their description, serve to explain the principles and operation of the invention.

The pump power monitor system and method of the present invention is adapted to optimize the pump power associated with an optical amplifier to meet required gain and gain ripple specifications. The gain and gain ripple specifications are maintained by monitoring the associated pump powers and error signals as deviated from a particular set point, which are fed back to a pump drive current powering each associated optical pump. It should be noted that

while the present invention pump power monitor method is discussed with respect to Raman amplification, it may be implemented in conjunction with other optical amplifiers including, but not limited to, erbium-doped fiber amplifiers operating at multiple wavelengths.

In the illustrated example, an optical fiber amplifier system 10 (Fig. 1) includes an optical pump 12 generating a pump radiation, as indicated by a directional arrow 13, to an optical wave guide amplifier 14 operating as an optical transmission fiber. As described herein, an amplifier system does not include a transmitting and/or receiving station, nor more than 1 km of transmission fiber that is not utilized for Raman amplification. As illustrated, optical pump 12 includes a Raman laser. For example, a semiconductor diode laser, a Raman fiber laser, or other laser emitting device may be substituted. It should be noted, that a plurality of laser emitting devices may be used simultaneously to provide amplification across a wide wavelength range as described below. Further, amplifier fiber 14 may also be utilized as a dispersion compensating fiber. The pump radiation or pump power 13 is transmitted to amplifier fiber 14 through optical tap 18. Optical pump 12 receives an electrical input as represented by a directional arrow 19 having both a DC electrical input component and an AC electrical input component. As a result, optical pump power 13 includes a DC optical pump power component and an AC optical pump power component.

An optical tap 18 diverts a portion of pump power 13 to a controller circuit 20 via an optical photodiode 16 and a trans-impedance amplifier 22. In the illustrated example, optical tap 18 includes a single, 1x2, fiber-based, 2% optical tap, however, other optical components capable of tapping a percentage of pump power 13 may be substituted. It should be noted, that digital equivalents to controller circuit 20 may be substituted therefore, as well as other analog circuitry described herein. The optical photodiode 16 operates as a pump power detector, provides a corresponding electrical signal to a trans-impedance amplifier 22, and provides an electrically equivalent signal of pump power 13 to controller circuit 20.

After pump power 13 has been detected and converted by trans-impedance amplifier 22, the electrically signal is proportional to $P_{DC} + m\cos(w_i)t$ where P_{DC} is the DC component of the optical pump power, m is the AC component of the optical pump power and ${}_i$ is the frequency of modulation of the i^{th} pump laser, the significance which will be described below. The electrically amplified signal is provided to a mixing circuit or mixer 24 where it is coupled

with a signal received from a local oscillator 26. Local oscillator 26 provides the modulation of the AC to both mixer 24 as well as to the AC electrical input component of electrical input 19 to optical pump 12 as described below. The mixed signal provided by mixer 24 is then detected by an amplitude detection circuit 28, which is in turn provided to a dividing circuit or divider 30. By frequency mixing the electrical signal provided by the trans-impedance amplifier 22 with local oscillator 26 having the same frequency, ω_i the signal going to divider 30 is proportional to m. A squaring circuit 32 squares the signal as provided by trans-impedance amplifier 22, thereby resulting in a signal that is proportional to $P_{DC}^2 + P_{DC} 2m\cos(w_1)t + m^2\cos^2(w_i)t$. The squared signal is then mixed with local oscillator 26 via a mixing circuit or mixer 34 and is then detected by an amplitude detection circuit 36, thereby providing a signal proportional to $2mP_{DC}$ at the output of the amplitude detection circuit 36. When one multiple local oscillator 26 are present, for multiple optical pumps (i.e., one oscillator for each pump), an additional path out of the trans-impedance amplifier is utilized. More specifically, an amplitude detection circuit 39 is used to detect the amplitude of the signal as provided by trans-impedance amplifier 22, which is in turn fed to a subtraction circuit where it is compared with the signal proportional to $2mP_{DC}$. The signal as provided by subtraction circuit 38 is then compared with the signal from amplifier protection circuit 28 via divider 30, thereby providing a final output signal that is proportional to P_{DC}.

The signal proportional to P_{DC} is then used to calculate the optimum power setting of optical pump 12. Specifically, the P_{DC} signal is fed to a subtraction circuit 42 where it is compared with a signal received from a power source 43 that is sent to optimize laser diode power set points, thereby resulting in a error signal as indicated by a directional arrow 44. The error signal 44 is fed to a scaling circuit 46. The power source 43 providing the laser diode power set points provides an optimized signal to a scaling circuit 48 and then to an adding circuit 50 where it is combined with the signal from scaling circuit 46. The DC output signal from adding circuit 50 is then combined with an AC signal as provided by local oscillator 26. Specifically, the AC signal provided by local oscillator 26 is fed to a scaling circuit 52, and the resulting signal is combined with the DC signal from adding circuit 50 via a

bias T circuit 54. This combined AC/DC signal from bias T 54 functions as electrical input signal 19 for optical pump 12, to precisely control pump 12.

In a preferred embodiment, a plurality of optical pumps are utilized to provide gain across a plurality of distinct wavelength ranges. Specifically, an optical fiber amplifier system 56 (Fig.2) includes a plurality of optical pumps 58, 60, 62,64, 66, and 68, similar to optical pump 12 described above with respect to amplifier system 10. As illustrated in Fig. 2, the optical outputs of optical pumps 58, 60, 62, 64, 66, and 68 are combined through polarization multiplexers and wavelength division multiplexers (WDMs). These pumps provide pump powers at four pump wavelengths and are preferably high power 14xx fiber Bragg grating stabilized, Fabry Perot semiconductor lasers. The optical pumps preferably have a small AC modulation at a frequency greater than 10 kHz. The electrical frequencies are provided by an oscillator(s) 26 to each of the optical pumps 58, 60, 62, 64, 66, and 68 and are preferably unique with an electrical frequency spacing between each pump that is unequal. These electrical frequencies have an amplitude of modulation preferably within the range of between about 10 mA to about 200 mA, and more preferably within the range of about 100 mA to about 200 mA. In the embodiment of Fig. 2, the oscillators 26 are contained in control circuits 88 through 98. It should be noted that the modulation frequency should be well separated to facilitate individual electrical filtering. In addition, the frequencies should be spaced to keep its filter band of a given amplitude detection circuit, that the frequencies should be greater than 10 kilohertz so as to avoid a transfer of any particular frequency component to the signals traveling in an opposite direction thereto, and that the magnitude of the current modulation should be great enough to facilitate detection thereof.

As illustrated, the pump power as provided by optical pumps 58 and 60 are at the same wavelength and orthogonally polarized, and is combined in a fiber-based polarization multiplexer 70. A similar combination of pump power as provided by optical pumps 62 and 64 is conducted via a fiber-based polarization multiplexer 72. As illustrated, pump powers having wavelengths with only one associated optical pump 66 and 68 are combined with a wavelength division multiplexer 74. The unpolarized light from the polarization multiplexers 70 and 72 are combined with a wave length division multiplexer 74′. In the illustrated example, a fiber-based wavelength division multiplexer 76, or possibly a micro-optic, is used to combine the pump power from optical pumps 58, 60, 62 and 64 with the pump power as provided by

pumps 66 and 68. In the present example, optical pumps 58, 60, 62 and 64 provide pump power within the wavelength range of between about 1400 nm to about 1510 nm, while optical pumps 66 and 68 provide pump power within the wavelength range of between about 1470 nm and 1510 nm. It should be noted that the operating wavelength ranges of optical pumps 58 through 68 may also include other wavelength ranges so as to amplify the entire S-band, C-band and L-band. Additional pumping wavelength ranges can be provided via a pump source 78 similar to that described above, and coupled with the output of wavelength division multiplexer 78 via an optical coupler 80.

The pump power as provided by optical pumps 58-68 and any additional pumping sources 78 are transmitted to an optical wavelength fiber 84 similar to amplifying fiber 14 described above. An optical tap coupler 86, similar to optical tap 18 described above, directs a portion of the pump power as provided by optical pumps 58-68 to a plurality of control circuits 88, 90, 92, 94, 96 and 98 via a trans-impedance amplifier 100, similar to transimpedance amplifier 22 as described above. Each control circuit 88-98 operates similarly to control circuit 20 as described above, thereby allowing precise control of the gain and gain ripple as introduced into a source signal traveling along fiber 84 by optical pumps 58-68. Each control circuit 88-98 includes an electrical oscillator with an unique modulation frequency. These oscillators apply different AC electrical input to their respective optical pumps and to their respective mixers.

The reference number 56a (Fig. 3) generally designates a second preferred embodiment of the present invention. Since amplifier system 56a is similar to the previously described amplifier system 56, similar parts appearing in Fig. 2 and Fig. 3 respectively are represented by the same, corresponding reference numeral, except for the suffix "a" in the numerals in the later.

In amplifier 56a, a control circuit 102, similar to control circuit 20 described above, receives an electrical signal from trans-impedance amplifier 100a and a local oscillator 104 similar to local oscillator 26 as described above. An adding circuit 106 receives the electrical output signal from control circuit 102 as well as an AC electrical input signal from local oscillator 104. The output signal of adding circuit 106 is fed to a 1x6 or six way electrical switch 108 that switches between six output lines associated with the optical pumps 58a-68a and is controlled by a clock timer that sequentially changes the output port of switch 108. The

output signal from switch 108 is forwarded to one of a plurality of adding circuits 112, 114, 116, 118, 120 and 122, associated with optical pumps 58a-68a, respectively, via a plurality of scaling circuits 124. The signals as received by adding circuits 112-122 are combined with the laser diode power set points as provided by a plurality of power sources 126, 128, 130, 132, 134 and 136, respectively, via a plurality of a scaling circuit 138.

The optical fiber amplifier systems as disclosed herein provide an optical and electrical configuration to obtain the pump power provided by each optical pump. These optical pump powers can be input into a controlling circuit as described herein, thereby insuring proper optical performance across different fiber types, within the manufacturing distribution of a signal fiber type, and within the manufacturing distribution and thermal range of the optical pumps utilized. It should generally be noted that while analog circuitry is described herein, digital components performing similar functions may be substituted therefore. It will become apparent to those skilled in the art that various modifications to the preferred embodiment of the invention as described herein can be made without departing from the spirit or scope of the invention as defined by the appended claims.

Example

In a first example (see Fig. 4), three distinct pump wavelengths were utilized to achieve 12 dB minimum gain and minimum gain ripple below 1 dB with typical LEAF™ fiber which is manufactured and available from Corning Incorporated of Corning, NY. Table 1 provides information on wavelengths and pump powers used in this example.

TABLE 1

Minimum Gain	Gain Ripple	Center Wavelengths		
		1461.2nm	**1477.8nm**	**1511.8nm**
12.1996	0.8996	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.1051	0.9694	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.2623	0.9831	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.1681	0.9601	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.2625	0.9732	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.168	0.95850	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.2833	0.9029	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW
12.2019	0.8678	1460.7nm209mW	1477.3nm181mW	1511.3nm210mW

In this example, the maximum pump power requirements are set by 12 dB minimum gain on LEAF™ fiber, if fiber with smaller effective areas are utilized, required pump powers for such fibers will be lower (Fig. 5). These figures illustrate that gain ripple performance can be maintained on such fibers with smaller effective areas by readjusting the pump powers.

More specifically, the optimum spectral gain dependence for a three wavelength, six pump diode LEAF™ fiber design of an additional example is shown in Fig. 4. In this example, pump powers have been adjusted to give 12 dB minimum gain across the signal spectrum with a gain ripple of 0.80 dB. Lowering and redistributing the pump power gives the gain spectrum for the small effective area fiber as shown on Fig. 5. The corresponding gain ripple at 12 dB minimum gain for this fiber is 0.89 dB. As illustrated, power re-optimization maintains gain ripple performance across different fiber types.

Along the same lines, the four (4) pump design of another example utilized a first pump at 1458.6 nm and 165 mW, a second pump at 1469.2 nm and 150 mW, a third pump at 1479.4 nm and 115 mW and a fourth pump at 1507.8 nm and 225 mW. This pumping scheme/system

results in a minimum gain to gain ripple ratio of 19.05, a minimum gain of 13.32 dB and minimum to maximum gain ripple difference of 0.699 dB. Fig. 6 illustrates the gain versus wavelength results of the four pump scheme/system.

Amplifier sensitivity to pump center wavelength tolerance was also determined by assuming a +/-0.5 nm center wavelength distribution, and modeling the 16 possible combinations of each pump having either +0.5 nm or -0.5 nm for the pump wavelength design corresponding to Fig. 6.

The worst combination of pump wavelength deviation from center values gives a ripple of 0.8 dB. While maintaining the pump wavelengths and readjusting the pump powers to 145 mW, 130 mW, 145 mW, and 225 mW, for the first, second, third and fourth pumps, respectively, a minimum gain of 13.19 dB and a gain ripple of 0.682 dB were obtained. The results of these examples clearly illustrates that control of pump power assists in maintaining gain ripple in the presence of the variations of pump center wavelength. It should further be noted that the control of pump power also assists in maintaining gain ripple within the manufacturing distribution of a single fiber type.

It will become apparent to those skilled in the art that various modifications to the preferred embodiment of the invention as described herein can be made without departing from the spirit or the scope of the invention as defined by the appended claims.